Wind resource assessment and economic analysis of a grid-connected wind farm in an Algerian Highlands site

Sabiha Kheder-Haddouche
Division Energie Eolienne
Centre de Développement des Energies Renouvelables
Algiers, Algeria
sabkheder@gmail.com

Djohra Saheb-Koussa
Division Energie Eolienne
Centre de Développement des Energies Renouvelables
Algiers, Algeria
d.saheb@cder.dz

***Abstract*— The purpose of this study is to assess the wind potential of Mecheria region and analyze the cost of the energy produced by a wind farm connected to the grid. Ten years of wind data (speed and direction) are analyzed using the WAsP software to obtain the annual wind characteristics A, k, V and P which take the values, respectively, 6.3 m/s, 1.83, 5.65 m/s and 224 W/m². The wind speed at 10m above ground level is mapped to find the windiest areas, and 2MW wind turbines from different technologies are erected to find the one that produces the highest Annual Energy (AEP).**

Finally, it is proposed, by using the HOMER software, to study the economic impact on the cost of kWh and Net Present Cost (NPC), due to the addition of a wind farm composed of V90-2MW wind turbines to a system totally dependent on the electrical grid. The environmental impact of harmful gas emissions is also evaluated.

The obtained results show that the optimal configuration to satisfy a demand of 431 MWh/d over a 40 MW capacity grid is a farm of 05 wind turbines, with a cost per kWh and an NPC respectively of $0.32 and $643537920 and renewable fraction (RF) of 23%. On another hand, the environmental impact is characterized by a reduction in CO2, SO2 and NOx emissions of 23%. The sensitivity analysis showed that the optimal system depends mainly on the wind speed.

Keywords*— *Wind resource, Economic, Environmental, Grid, WAsP, HOMER.

I. Introduction

Although fossil fuels are still ubiquitous in the global energy mix, the share of renewable energy is growing steadily. Regarding wind power, Europe, which has been a pioneer in its development, has been overtaken by Asia and North America, which have largely led the procession and consecrated permanently this type of energy as a source of electricity production [1].

Thus, worldwide, installed wind capacity in 2017 amounted to 52.6 GW. In addition, there are sharp falls in production costs in countries as diverse as Morocco, India, Mexico and Canada with projects at $ 0.03 / kWh and a recent tender in Mexico below $ 0.02/kWh. According to the latest data from the IEA (International Energy Agency), the global wind farm produced 838 TWh in 2015, just over 3% of the world's electricity generation that year [2].

As for Algeria, which is facing the crisis caused by the sharp fall in oil prices, the main source of its revenues, the country must implement the program for renewable energy that the government drew in 2015 [3], which plans to integrate 5GW wind power generation by 2030.

Indeed, over the years and in the direction of socio-economic development where the needs for electric energy is increasing, wind applications appear prominently as a source of backup energy to conventional sources. On the other hand, Algeria has a significant wind potential for which many studies have been conducted to quantify it, through various tools such as AIOLOS and WAsP models, [4-12].

In this sense, the latest atlas realized by the CDER [12] reveals a significant number of sites with considerable wind energy potential that can be exploited for the implementation of large wind projects.

Through this atlas, we can observe the existence of windy areas all along the Saharan Atlas. It is to be noted that, in addition to the sites in the southern region such as Adrar, In Salah and Tindouf, Mecheria region also seems to have a significant wind energy potential. Indeed, on the basis of the data measured at 10 m height from the ground level and provided by the National Office of Meteorology (ONM), this region has an average annual speed of about 5.30 m/s, average speed which could reach or exceed 7m/s at a height of 80m.

Thus, these results can be viewed as incentive for integrating the produced wind energy into the electric grid. To do this, the economic indicator should be taken into account in order to confirm the feasibility of such an application. So, the determination of the cost per kilowatt hour produced will be an important indicator of the eligibility for the wind farms installation. For this purpose, several studies have been carried out including [13-20].

So, in this present study: In the first part, the WAsP software is used to determine the relative wind potential of the region whose geographic coordinates range in between the latitudes 33.35 ° and 33.95 ° and the longitudes in between-0.55 ° and 0.2°. In the windy areas of this region, the estimated annual average velocity exceeds 8 m/s at 80m height

978-1-5386-6933-4/18/$31.00 ©2018 IEEE

from the ground level. In addition, in order to analyze the grid-connected wind farm system, it is deemed necessary to evaluate the annual energy that would be produced by four (04) models of wind turbines whose rated capacity is 2MW each, and based on different technologies.

In the second part, based on the results obtained through the first part, we used HOMER software to perform the technical-economic and environmental analysis of a wind farm connected to the grid, and consisting of five (05) 2MW wind turbines. The simulations carried out make it possible to calculate the cost per kWh of the electrical energy produced by various configurations (standard grid and grid-connected wind farm) under certain constraints (load, capacity of the grid, limit of the injection to the grid). The obtained results give the best configuration with the optimal number of wind turbines. The environmental impact is represented by the emission rates of the different gases.

II. Wind Assessment

A. Data and tools

1) *Description of the site:* Mecheria is located in the northeastern province of Naama, Algeria, Fig. 1.
It is considered as one of the crossroads that connect southern Algeria to Oran. It covers an area of 736.25 km2.

It lies between the Tell Atlas and the Saharan Atlas, and is part of the Western Highlands. It is characterized by a flat northern steppe zone and a mountainous area forming part of the Saharan Atlas.

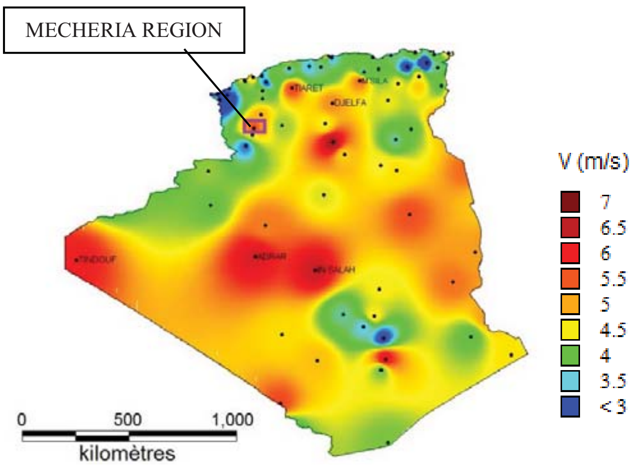


Fig.1. Location of Mecheria region [12]

2) *Wind data:* This study is based on three-hour wind speed and direction measurements over a period of 10 years from 2007 to 2016 collected at 10m height from the ground level at Mecheria meteorological station (Table I).

TABLE I. Description and Geographical Coordinates of Station of Mecheria

Station name	Latitude (deg)	Longitude (deg)	Recording period	Elevation (m above sea level)
MECHERIA (at 10m a.g.l.)	33.536	-0.242	2007-2016	1111.1

3) *Topographical and surface data:* The elevations used field comes from the database SRTM3 ("Shuttle Radar Topographical Mission") 3 seconds of arc resolution, corresponding to approximately 90 meters of resolution, [21].

The contours were drawn at intervals of 40 m. The digital terrain model was extracted using the Global Mapper software and the map of elevations contours is drawn with SURFER software (Fig. 2).

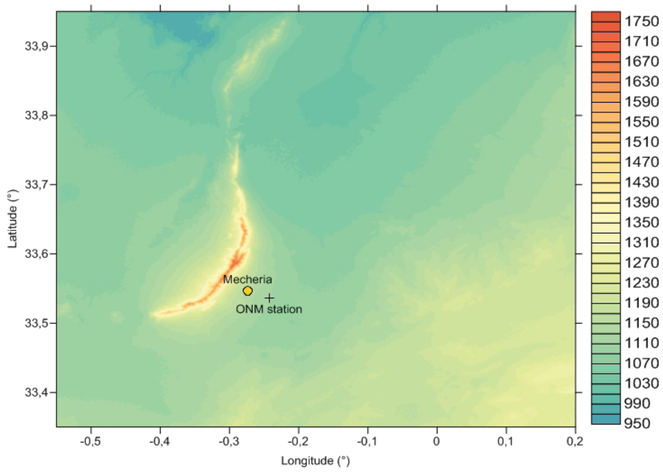


Fig. 2. Elevation map of the region of Mecheria

The surface will always influence the wind through the roughness of the terrain. This work was performed for the whole studied region, where the roughness lengths vary from 0.003 to 0.5m.

B. Methodology

For the simulation, we used the WAsP (Wind Atlas Analysis and Application Program) software, of Riso National Laboratory (N.G. Motersen et al., 1993). WAsP is a dynamical model based on the theory of Jackson and Hunt. It takes into account the effect of different roughness conditions, sheltering effects due to nearby buildings and other obstacles, and modification of the wind characteristics imposed by hills and complex terrain.

Providing a prediction in the Mecheria region will therefore be a two-stage process. First, the data from the meteorological station need to be analyzed to produce a wind atlas, and then the resulting wind atlas needs to be applied to the proposed turbine site to estimate the wind power [22].

The Wind Atlas for Mecheria has made extensive use of Shuttle Radar Topography Mission elevation data for constructing detailed height contour maps around the station,

and of satellite imagery(Google Earth) for mapping the land-use and surface roughness conditions.

The wind resource mapping of the studied region at a height of 10 meters a.g.l. is performed by WASP software to find windy areas. In order to set up a wind farm in Mecheria region, four (04) models of wind turbines from different technologies and whose rated capacity is 2MW each, are selected. Their characteristics are given in Table II.

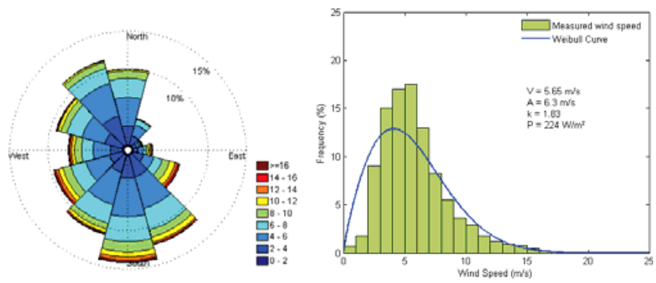
TABLE II. CHARACTERISTICS OF THE SELECTED WIND TURBINES

Wind Turbine	***Rated Capacity (kW)***	***Rotor Diam. (m)***	***Hub Height (m)***	***Cut-in Speed (m/s)***	***Rated Speed (m/s)***	***Cut-out Speed (m/s)***
Bonus-2MW	2000	76	60	4		25
NEG-Micon2000-500/72	2000	72	67	4		25
VestasV80-2MW	2000	80	68	4		25
Vestas V90-2MW	2000	90	80	4	14	25

C. Results and discussions

The wind data has been analyzed using the WAsP software. Thus, the local wind resource is characterized by statistical parameters such as Weibull parameters A (scale factor) and k (form factor), as well as annual average speed V and power density P. As can be seen in Fig.3(b), the two first are 6.3 m/s and 1.83 respectively, while U and P are 5.65 m/s and 224 W/m². The fairly high value of A denotes an appreciable wind while k which is close to 2 represents a steady wind. The wind rose for the Mecheria station at 10m a.g.l. is illustrated *in* Fig.3(a), where it is noticed that the prevailing wind directions are North-West with a value of 11.7%, South-East with 12.3% and South with 14.2%.

Fig.4 shows the monthly distribution of wind speeds, estimated on the basis of data measured at the meteorological station in Mecheria. We note that the highest speed values are observed in winter particularly in February and March, while the lowest are found in summer in August.



(a) (b)

Fig. 3. (a) Wind rose diagram at a height of 10m, (b) Weibull distribution (A = 6.3 m/s and k = 1.83) and histogram

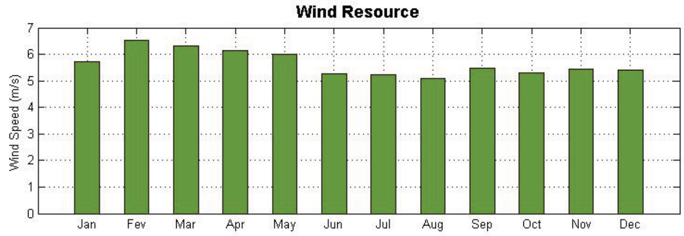


Fig. 4. Monthly speed distribution, obtained from wind data measuring at 10 m a.g.l.

Resource grids at different heights (10, 60, 67, 68 and 80m) are calculated using the WAsP software.

The wind turbine model, the Weibull parameters, the mean wind speed, the annual mean power density and the annual energy produced are given in Table III.

Fig.5 shows the mean wind speed distribution through the selected site for erecting the wind turbine. It can be observed that the mean wind speed at 80 m ranges between 7.9 and 8.9 m/s. These results show that the region of Mecheria is suitable for installing a wind farm.

TABLE III. CHARACTERISTICS OF THE SELECTED WIND TURBINES

Wind Turbine	***A (m/s)***	***K***	***V (m/s)***	***P (kW/m²)***	***AEP (GWh)***
Bonus-2MW	9.1	2.16	8.04	566	6.607
NEG-Micon2000-500/72	9.3	2.19	8.26	605	6.520
VestasV80-2MW	9.3	2.19	8.23	600	7.334
Vestas V90-2MW	9.6	2.23	8.54	657	9.003

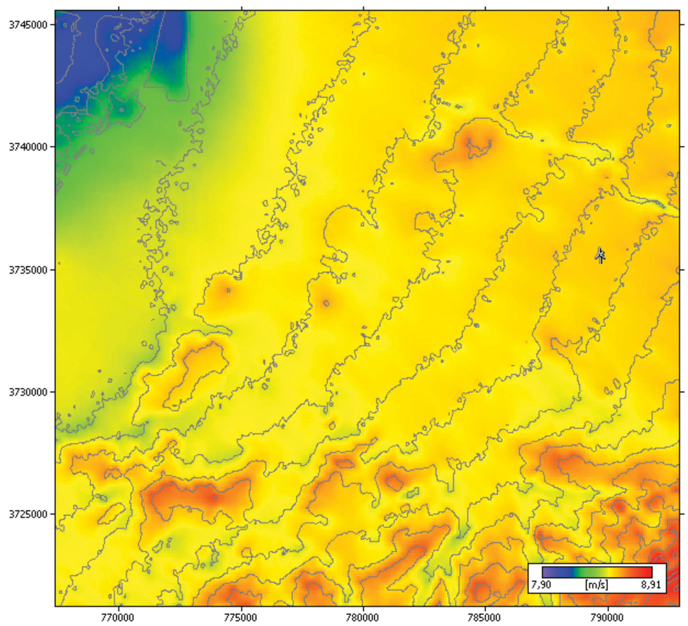


Fig. 5. Mean wind speed Map at 80m a.g.l. in Mecheria

III. Economic and Environmental Analysis

A. *The HOMER Tool*

The present study was conducted using the HOMER software developed by the National Renewable Energy Laboratory (NREL, 2004). It is an economic optimization model that minimizes the production costs of an energy park to meet a final energy demand, under different constraints.

As inputs, the techno-economic parameters of the considered technologies (annual real interest rate, project lifetime, etc.), as well as the environmental characteristics of the considered location (wind, etc.) are needed. On another hand, various constraints as the renewable energy fraction and the monthly mean of hourly load demand are also needed.

As output data, the HOMER tool classifies the results according to the total Net present cost per kWh over the project lifetime. The software tool is also used to describe the hourly system's behavior over a whole year and used particularly to integrate the intermittent nature of wind generation [23].

HOMER uses the following equation to calculate the total net present cost [24]:

$$C_{NPC} = \frac{C_{ann\_tot}}{CRF(i, R_{proj})} \quad (1)$$

Where: Cann_tot is the total annualized cost, [$/year]
i the annual real interest rate (the discount rate),
Rproj the project lifetime, [year]
and CRF(.) is the capital recovery factor, given by the equation:

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (2)$$

where i is the annual real interest rate and N is the number of years.

In this study, various configurations are considered and presented for the grid-connected wind system with a comparison to the "grid only" configuration for which sensitivity analyzes were also performed.

1) The realized system: Fig.6 shows the diagram of wind farm as realized in HOMER Software.

2) The input parameters: Informations about the input parameters required by HOMER software are as specified below:

a) *Electrical load:* The daily load profile used in this work is assumed to be constant over the year. Thus, this latter is presented in Fig.7 which presents an average value of 431 MWh/day and a peak of 27 MW.

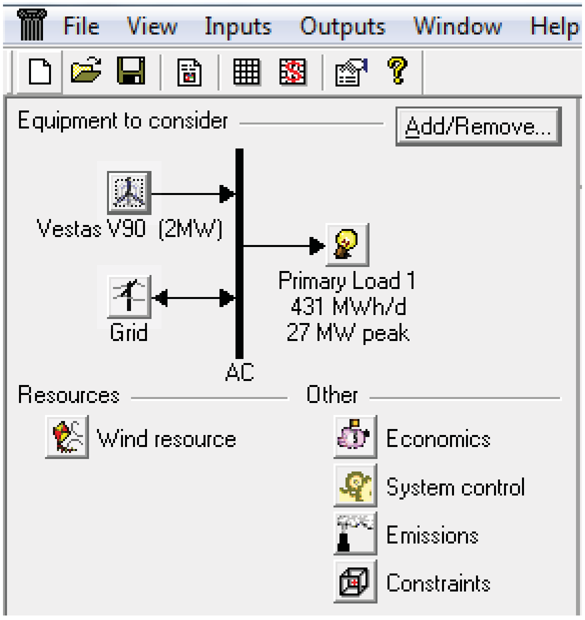


Fig.6. Proposed wind farm in HOMER

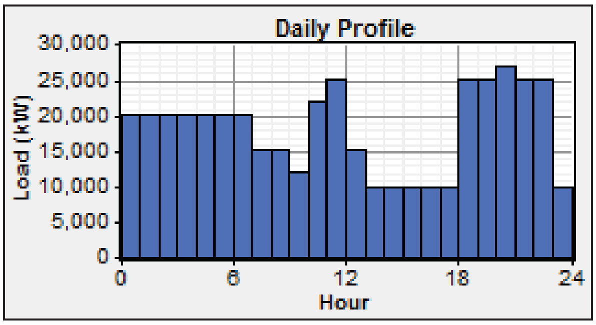


Fig. 7. Daily load profile

b) *Wind turbine:* To do the simulation work, the retained wind turbine is the Vestas V90-2MW. The corresponding technical characteristics are presented in Table IV.

Thus, by considering the latters and using a speed value of 8.54 m/s at 80m a.g.l., the Vestas V90-2MW produces an annual energy (AEP) of 9.003 GWh.

TABLE IV. Characteristics of the Used Wind Turbine

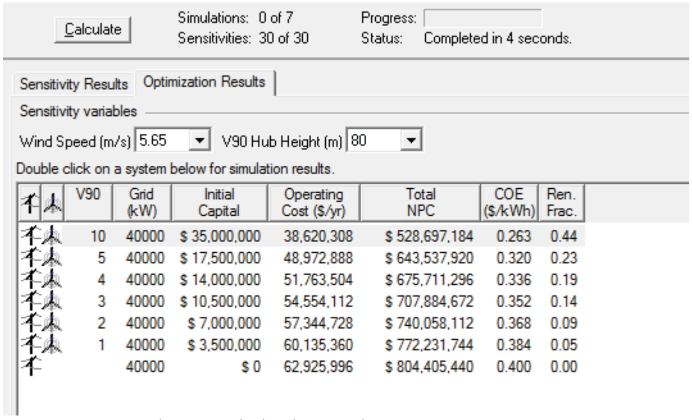
Wind Turbine	*Rated Capacity (kW)*	*Rotor Diam. (m)*	*Hub Height (m)*	*Cut-in Speed (m/s)*	*Rated Speed (m/s)*	*Cut-out Speed (m/s)*
Vestas V90-2MW	2000	90	80	4	14	25

c) *The characteristics of the considered Grid:* The main grid characteristics data needed as inputs in HOMER software to simulate the different system configurations are as follows :

Grid capacity : 40000kW.
Grid power price : 0.4$/kWh.

B. Results and discussions

1) Optimization results: From the results presented in Fig.8, it's observed that the most interesting configuration in term of economic indicator is that of the wind farm. This consisting of 10 wind turbines, connected to the grid and which represents lowest total NPC and the COE values of $ 528 697 184 and $ 0.263 / kWh respectively, and for which the Renewable energy fraction takes its maximum value of 0.44.



V90	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.
10	40000	$ 35,000,000	38,620,308	$ 528,697,184	0.263	0.44
5	40000	$ 17,500,000	48,972,888	$ 643,537,920	0.320	0.23
4	40000	$ 14,000,000	51,763,504	$ 675,711,296	0.336	0.19
3	40000	$ 10,500,000	54,554,112	$ 707,884,672	0.352	0.14
2	40000	$ 7,000,000	57,344,728	$ 740,058,112	0.368	0.09
1	40000	$ 3,500,000	60,135,360	$ 772,231,744	0.384	0.05
	40000	$ 0	62,925,996	$ 804,405,440	0.400	0.00

Fig. 8. Opimization results

So, even though this latter configuration presents the most best performances, given that the power injected into the Algerian power grid must not exceed 25% of the total produced power, it follows that the configuration with 10 wind turbines is to be excluded. However, the one with 05 wind turbines represents the optimal solution. In this case, the renewable energy fraction is 23% (Fig. 9).

Emissions have very negative impact on the environment and result from gaz consumption. By carrying out a comparison between various retained configurations, it can be found that maximum emissions rates result from systems operated only by standard grid system and decrease when the wind turbines number increases as shown in Table V in which are presented the CO2, NOx and SO2 production levels for the different retained configurations.

2) *Sensitivity results :* In this study, to observe how the variations in wind speed and wind turbine tower height affect the optimal system design, the HOMER sensitivity analysis is considered, with the electric kWh price set at 0.4$. From the results presented in Fig. 10, it is observed that the optimal system design depends on the average wind speed value and that the Grid-Wind system becomes optimal only from V = 5.65 m / s. On the other hand, it is observed that it is independent from the height of the wind turbines tower.

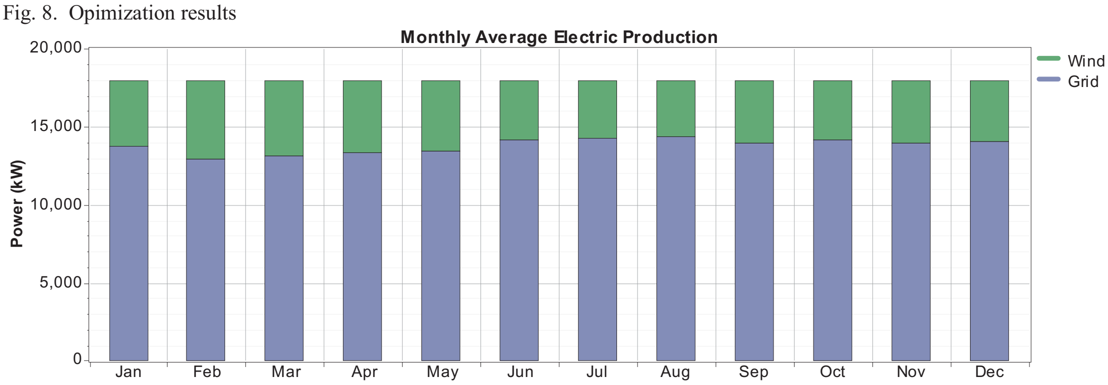


Fig. 9. Monthly average electric production of the system Grid-Wind (05 wind turbines)

TABLE V. EMISSIONS OF GASES OF THE DIFFERENT CONFIGURATIONS PROPOSED BY THE HOMER SOFTWARE

Types of pollutants (kg/year)	**Standard grid**	**Wind-grid system Number of wind turbines**					
		1	2	3	4	5	10
CO_2	99 423 064	94 811 656	90 200 256	85 588 864	80977496	76366128	53 309 168
NO_x	210 802	201 025	191 247	181 470	171 693	161 916	113 029
SO_2	431 043	411 051	391 058	371 066	351 073	331 081	231 119

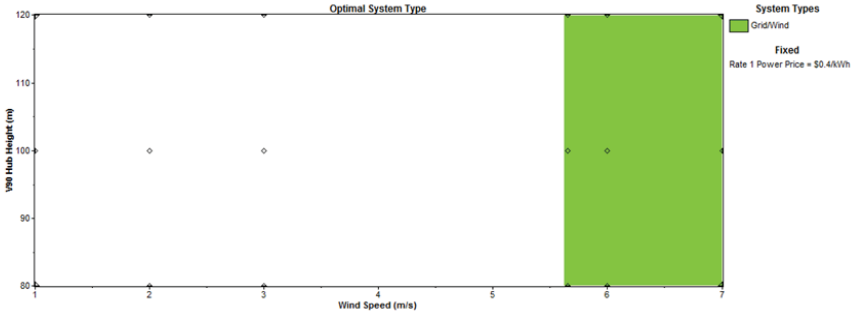


Fig. 10. Optimal system type

IV. Conclusion

This work focuses on the possibility of setting up a wind farm connected to the network in the Mecheria region. The WAsP deposit study determined annual the mean velocity and average annual power density values at 10m height from the ground, which are 5.65 m/s and 224 W/m², respectively. With a speed of 8.54 m/s at 80m above the ground level, the chosen wind turbine, is the Vestas V90-2MW, which presents an annual energy production of 9.003 GWh.

The HOMER software is used to perform an economic analysis which leads to determining the optimal wind farm configuration of 05 wind turbines, with $ 0.4 as a price of the produced electric kWh and a constraint of 25% of the total capacity injection into the grid. On another hand, the uses of this system leads to reducing the COE to $ 0.32 per kWh with a fraction in renewable energies of the order of 23%. The environmental analysis shows that CO_2, SO_2 and NO_x emissions in this system decrease by 23%.

The sensitivity analysis shows that the optimal system depends on the annual average speed of the site: the Grid-Wind system (Farm of 05 wind turbines connected to the grid) is optimal only for a speed greater than or equal to 5.65 m/s.

References

[1] https://unfccc.int/fr/news/lenergie-eolienne-en-croissance-dans-le-monde

[2] https://www.connaissancedesenergies.org/leolien-en-europe-et-dans-le-monde-en-2017-180214GLOBAL WIND ENERGY COUNCIL
http://gwec.net/global-figures/graphs/

[3] CREG. (2015). Programme de Développement des Energies Renouvelables 2015-2030.

[4] K. Abdeladim, R. Romeo and S. Magri, Wind mapping of a region in the north-east of algeria, , WREC 1996, (1996) 789-793.

[5] N. Kasbadji Merzouk, Wind energy potential of Algeria, Renew Energy 21 (2000), pp. 553–562.

[6] N. Kasbadji Merzouk , H. Daaou and S. Haddouche, Evaluation of wind energy potential for windy micro-area using mass consistent model, world renewable energy conference WREC2002, Allemagne juin 2002.

[7] H. Daaou Nedjari, S. Haddouche and N. Kasbadji Merzouk, Caractérisation éolienne de sites ventés à l'aide du modèle AIOLOS et d'un modèle numérique de terrain (MNT), Revue des Energies Renouvelables SMEE'10 Bou Ismail Tipaza (2010) 135 – 142.

[8] R. Hammouche, Atlas Vent de L'Algerie, Publication interne de l'Office National de Météorologie, 1990.

[9] A. Adjiri, H. Daaou Nedjari and S. Kheder Haddouche, Estimation du potentiel éolien pour la région d'In Salah, Revue des Energies Renouvelables Vol. 16 N°4 (2013) 657 – 666.

[10] S. M. Boudia and O. Guerri, Investigation of wind power potential at Oran, northwest of Algeria, Energy Conversion and Management 105 (2015) 81-92.

[11] Abdeslame D, Kasbadji N, Mekhtoub S, Abbas M, Dehmas M. Estimation of power generation capacities of a wind farms installed in windy sites in Algerian high plateaus. Renew Energy 2017;103:630e40.

[12] H. Daaou Nedjari, S. Kheder Haddouche, A. Balehouane and O. Guerri, Optimal windy sites in Algeria : Potential and Perspectives, Energy 147 (2018) 1240-1255.

[13] A. Al-Sharafi, A. Z. Sahin, T. Ayar and Bekir S. Yilbas, Techno-economic analysis and optimization of solar and wind energy systems for power generation and hydrogen production in Saudi Arabia, Renewable and Sustainable Energy Reviews, 69, (33), (2017).

[14] D. Saheb Koussa and M. Koussa, GHGs (greenhouse gases) emission and economic analysis of a GCRES (grid-connected renewable energy system) in the arid region, Algeria, Energy 102 (2016): 216-230.

[15] D. Saheb Koussa and M. Koussa, A feasibility and cost benefit prospection of grid connected hybrid power system (wind–photovoltaic)–Case study: An Algerian coastal site, Renewable and Sustainable Energy Reviews 50 (2015): 628-642.

[16] M. Munday, G. Bristow and R. Cowell, Wind farms in rural areas: How far do community benefits from wind farms represent a local economic development opportunity?, Journal of Rural Studies 27.1 (2011): 1-12.

[17] J. Atherton, R. Sharma and J. Salgado, Techno-economic analysis of energy storage systems for application in wind farms, Energy 135 (2017): 540-552.

[18] M. Satir, , F. Murphy and K. McDonnell. "Feasibility study of an offshore wind farm in the Aegean Sea, Turkey, Renewable and Sustainable Energy Reviews (2017).

[19] R. Villena-Ruiz and al, A techno-economic analysis of a real wind farm repowering experience: The Malpica case, Energy Conversion and Management 172 (2018): 182-199.

[20] L. Stougie and al., Environmental, economic and exergetic sustainability assessment of power generation from fossil and renewable energy sources, International Journal of Energy Research (2018).

[21] Shuttle Radar Topography Mission (SRTM), NASA, 1987. http://www2.jpl.nasa.gov/srtm/.

[22] Wind Atlas Analysis and Application Program (WAsP), Risø National Laboratory, 1987. http://www.wasp.dk/.

[23] P. Menanteau, M. Quéméré, A.Le Duigou, S. Le Basetard, Une analyse économique de la production d'hydrogène à partir d'électricité éolienne pour des usages transport, Revue de l'Energie, 2010, 61 (597), pp.322-333.

[24] T. Lambert, P. Gilman and P. Lilienthal, Micropower System Modeling With Homer, Wiley-IEEE Press, 2006, **ISBN :**9780471755623, 408 pages.